Supersymmetric $U(1)'$ Models

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In collaboration with
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and Itay Yavin

PRL **100** 041802	(2008)	[arXiv:0710.1632]
PRD **77** 085033	(2008)	[arXiv:0801.3693]
PLB **671** 245	(2009)	[arXiv:0811.1196]
SUSY 2009 Proceedings		[arXiv:0910.2480]
JHEP **1001** 037	(2010)	[arXiv:0911.1996]

Motivation

- High(er) energy models (e.g. superstring constructions) often involves extra $U(1)'$

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- Mediation mechanism of SUSY breaking determines the low energy phenomenology

Reminder

- MSSM superpotential

$$W = y_u H_u Q u^c + y_d H_d Q d^c + y_e H_d L e^c + \mu H_u H_d$$

- Soft susy breaking Lagrangian (schematically)

$$\begin{aligned}
\mathcal{L}_{\text{soft}} \quad \ni \quad & -\frac{1}{2}\, m^2 \phi\, \phi^\dagger && \text{(scalar masses)} \\
& -\frac{1}{2}\, M\, \tilde{\lambda}\, \tilde{\lambda} && \text{(gaugino masses)} \\
& -\frac{1}{6}\, A\, \phi_i\, \phi_j\, \phi_k && \text{(A terms)} \\
& -\frac{1}{2}\, b\, \phi_i\, \phi_j \\
& + \quad h.c.
\end{aligned}$$

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\end{aligned}$$

- Why should SUSY-conserving μ be related to SUSY-breaking m^2 and b ?

  Large $\tan\beta$ limit: $M_Z^2 = -2(m_{H_u}^2 + |\mu|^2) + \ldots$

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- Mediation mechanism of SUSY breaking determines the low energy phenomenology

- MSSM μ problem

- $U(1)'$ models offer a solution

Reminder

- If H_u, H_d charged under $U(1)'$, **forbid** $\mu H_u H_d$
- Superpotential

$$W = y_u H_u Q u^c + y_d H_d Q d^c + y_e H_d L e^c + \lambda S H_u H_d$$

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\end{aligned}$$

- $\mu_{\rm eff} = \lambda \langle S \rangle$ can be related to SUSY-breaking m^2 and b

Motivation

- High(er) energy models (e.g. superstring constructions) often involves extra $U(1)'$
- Mediation mechanism of SUSY breaking determines the low energy phenomenology
- MSSM μ problem
- $U(1)'$ models offer a solution

Outline

- Z' mediation - Mediating SUSY breaking using $U(1)'$
  - General features
  - Specific implementation

    Paul Langacker, GP, Lian-Tao Wang, Itay Yavin

    PRL **100** 041802 (2008) [arXiv:0710.1632]

    PRD **77** 085033 (2008) [arXiv:0801.3693]
- Combining Anomaly and Z' mediation
  - General features
  - Specific implementation

    Jorge de Blas, Paul Langacker, GP, Lian-Tao Wang

    Preliminary results: [arXiv:0910.2480]

    JHEP **1001** 037 (2010) [arXiv:0911.1996]
- General issues with SUSY $U(1)'$ models
  - Accidental symmetries
  - Vacuum structure

    Paul Langacker, GP, Itay Yavin

    PLB **671** 245 (2009) [arXiv:0811.1196]

Z' Mediation of SUSY Breaking

Paul Langacker, GP, Lian-Tao Wang, Itay Yavin

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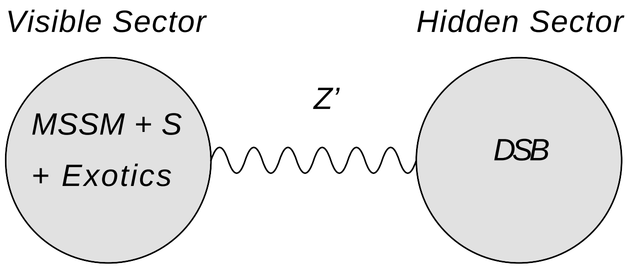
Sectors

- No direct renormalizable interaction between visible and hidden sector fields

- **Both** are charged under $U(1)'$



- At Λ_S the Z' gaugino becomes massive

- How are MSSM fields affected?

Reminder

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\end{aligned}$$

Masses

- Gaugino $\tilde{\lambda}_i$ decouple when $g_i \to 0$

  $\Rightarrow$ To "feel" SUSY breaking all masses must be $\propto g_{z'}^2$

- Scalar masses

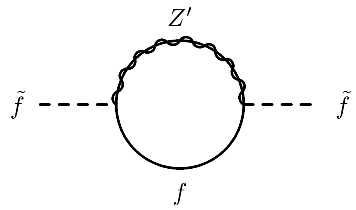
$$m_{\tilde{f}_i}^2 \propto g_{z'}^2$$

- $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauginos' masses must be also $\propto g_a^2$

$$M_a \propto g_{z'}^2 g_a^2$$

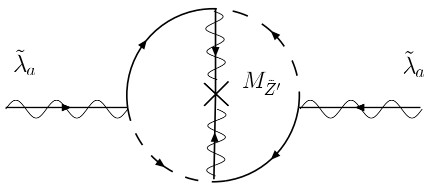
Masses

- Scalars get a mass at one loop



$$m^2_{\tilde{f}_i} \sim g^2_{z'} Q^2_{f_i} \frac{M^2_{\tilde{Z}'}}{16\pi^2} \log\left(\frac{\Lambda_S}{M_{\tilde{Z}'}}\right)$$

- $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauginos get a mass at two loops



$$M_a \sim g^2_{z'} g^2_a \frac{M_{\tilde{Z}'}}{(16\pi^2)^2} \log\left(\frac{\Lambda_S}{M_{\tilde{Z}'}}\right)$$

- Ratio of masses

$$\frac{m_{\tilde{f}_i}}{M_a} \sim \frac{M_{\tilde{Z}'}}{4\pi} \Big/ \frac{M_{\tilde{Z}'}}{(4\pi)^4} = (4\pi)^3 \sim 1000$$

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- LEP direct searches imply EW-ino mass > 100 GeV
- Two options:

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  1. Scalars at EW scale ($\sim 100 - 1000$ GeV)

     $\Rightarrow$ gauginos too light, must acquire mass from other mechanism

     e.g combine "Anomaly" with Z'

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  1. Scalars at EW scale ($\sim 100 - 1000$ GeV)

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     e.g combine "Anomaly" with Z'
  2. Gauginos at EW scale ($\sim 100 - 1000$ GeV)

     $\Rightarrow$ heavy scalars ~ 100 TeV $\Rightarrow M_{\tilde{Z}'} \sim 1000$ TeV

  – Mini version of split-susy (Arkani-Hamed & Dimopoulos 2004)

    split susy scalar mass 10^9 GeV

  – Like split-susy no flavor or CPV problems due to heavy scalars

  – Like split-susy need one fine-tuning to set EW breaking scale

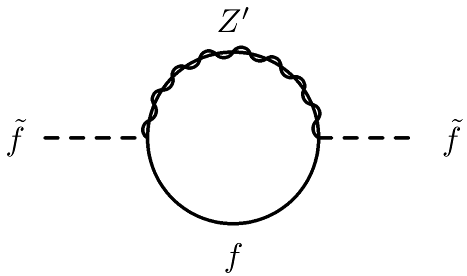
  – Unlike split-susy μ parameter scale set by $U(1)'$ breaking

Elements of Z' mediation

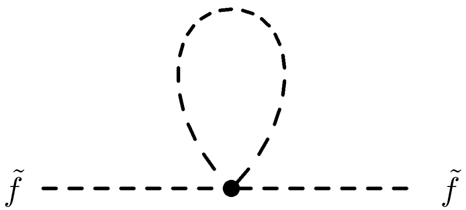
- To break the $U(1)'$ symmetry introduce SM singlet field (charged under $U(1)'$)
- $\mu\, H_u\, H_d \;\rightarrow\; \lambda\, S\, H_u\, H_d$
- Include exotic matter $\sum_i y_i\, S\, X_i\, X_i^c$
  - Cancel anomalies associated with $U(1)'$
  - Drive S negative

Driving S negative

- Scalar mass RGE has contributions from various diagrams



$$\Rightarrow \qquad \frac{dm_S^2}{dt} = -8 g_{z'}^2 Q_S^2 M_{\tilde{Z}'}^2$$



$$\Rightarrow \qquad \begin{aligned} \frac{dm_S^2}{dt} &= 4\lambda^2 (m_S^2 + m_{H_u}^2 + m_{H_d}^2) \\ &+ y_i^2 (m_S^2 + m_{X_i}^2 + m_{X_i^c}^2) \end{aligned}$$

- At $t = 0$ gauge term drives m_S positive

  As t becomes more negative, m_i grow and at some point m_S goes negative

Higgs mass matrix

- Scalar S potential

$$V(S) = \underset{\substack{\uparrow \\ \text{Rad. Gen.}}}{m_s^2|S|^2} + \underset{\substack{\uparrow \\ D\text{ term}}}{\tfrac{1}{2}g_{z'}^2 Q_S^2|S|^4}$$

- VEV of S

$$\langle S\rangle = \left|\frac{m_S}{g_{z'}Q_S}\right|$$

- Higgs mass matrix

1) "M" terms: $m_{H_u}^2$, $m_{H_d}^2$ from RGEs

2) F terms: $\lambda^2 S^2 H_i^2 \Rightarrow \lambda^2\langle S\rangle^2$

3) D terms: $\frac{1}{2}g_{z'}^2(Q_2 H_u^2 + Q_1 H_d^2 + Q_S S^2)^2 \quad \Rightarrow \quad g_{z'}^2\langle S\rangle^2 Q_S Q_i$

4) A terms: $ASH_uH_d \quad \Rightarrow \quad A\langle S\rangle H_u H_d$

Higgs mass matrix

- Higgs mass matrix

$$\mathcal{M}_H^2 = \begin{pmatrix} m_2^2 & -A_H\langle S\rangle \\ -A_H\langle S\rangle & m_1^2 \end{pmatrix}$$

$$\begin{aligned} m_2^2 &= m_{H_u}^2 + g_{z'}^2 Q_S Q_2 \langle S\rangle^2 + \lambda^2\langle S\rangle^2 \\ m_1^2 &= m_{H_d}^2 + g_{z'}^2 Q_S Q_1 \langle S\rangle^2 + \lambda^2\langle S\rangle^2 \end{aligned}$$

- To generate $\Lambda_{\rm EW}$ must fine-tune linear combination of H_i to be much lighter than natural scale
- Typically find solutions by tuning $|m_2^2| \ll m_1^2 \sim g_{z'}^2 M_{\tilde{Z}'}^2/16\pi^2$
- $\tan\beta \approx m_1^2/A_H\langle S\rangle \sim 10 - 100$
- Get single SM-like Higgs scalar, with mass ∼140 GeV.
- Remaining Higgs particles are at ∼ 100 TeV

“Beyond MSSM” Masses

“Beyond MSSM” particles:

- Exotic superfield

$$W \ni \sum_i y_i \, S \, X_i \, X_i^c$$

Exotic superfield mass: $y_i \langle S \rangle \quad \surd$

- Z' superfield
  - $\tilde{Z}'$ gaugino: $M_{\tilde{Z}'} \quad \surd$
  - Z' gauge boson ?
- S superfield
  - scalar $\langle S \rangle \quad \surd$
  - fermion - Singlino - $\widetilde{S}$?

Non-scalar masses

- As a result of S getting a VEV, Z' gauge boson gets a mass from $U(1)$ Higgs mechanism

$$M_{Z'} = \sqrt{2} g_{z'} |Q_S| \langle S \rangle$$

- The singlino $\widetilde{S}$ receives a mass via mixing with $\tilde{Z}'$

$$\mathcal{L} = -\sqrt{2} g_{z'} (S\, Q_S\, \widetilde{S}) \tilde{Z}'$$

Singlino Z'-ino mass matrix

$$\mathcal{M}_{SZ} = \begin{pmatrix} 0 & -\sqrt{2} g_{z'} Q_S \langle S \rangle \\ -\sqrt{2} g_{z'} Q_S \langle S \rangle & M_{\tilde{Z}'} \end{pmatrix}$$

Eigenvalues given by usual seesaw formula

$$\mathcal{M}^{(1)}_{SZ} = -\frac{M^2_{Z'}}{M_{\tilde{Z}'}} \qquad \mathcal{M}^{(2)}_{SZ} = M_{\tilde{Z}'}$$

General features - Summary

- High energy spectrum $g_{z'} \sim \lambda \sim (0.1 - 1)$:

  Z'-ino mass $M_{\tilde{Z}'} \sim 1000$ TeV

  Typical scalar mass $m_{\tilde{f}_i} \sim 100$ TeV

  $\langle S \rangle \sim M_{\tilde{Z}'}/4\pi \sim 100$ TeV

  $\mu = \lambda \langle S \rangle \sim 10 - 100$ TeV

  Exotic superfield mass $y_i \langle S \rangle \sim 10 - 100$ TeV

  $M_{Z'} = \sqrt{2} g_{z'} Q_S \langle S \rangle \sim 10 - 100$ TeV

  $M_{\tilde{S}} = \frac{M_{Z'}}{M_{\tilde{Z}'}} M_{Z'} \sim 1 - 10$ TeV

- Low energy spectrum

  SM + Higgs + $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauginos

General features - Summary

- Interesting case for $g_{z'} \ll \lambda$

$$|M_{H_u}|^2 \sim \frac{g_{z'}^2 M_{\tilde{Z}'}^2}{16\,\pi^2} \text{ tuned against } \lambda^2 \langle S \rangle^2$$

$$\Rightarrow \langle S \rangle \sim \frac{g_{z'}}{\lambda} \frac{M_{\tilde{Z}'}}{4\pi}$$

$$M_{\tilde{S}} \sim \frac{g_{z'}^2 Q_S^2 \langle S \rangle^2}{M_{\tilde{Z}'}} \sim g_{z'}^2 \frac{g_{z'}^2}{16\,\pi^2} M_{\tilde{Z}'}$$

  – Very light singlino $M_{\tilde{S}} \sim \left(10^{-3} - 10^{-5}\right) M_{\tilde{Z}'}$

  – Z' gauge-boson, $M_{Z'} \sim g_{z'} Q_S \langle S \rangle$, in this case can be light enough to be produced @ LHC

- Low energy spectrum

  SM + Higgs + $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauginos +

  + Singlino and even Z'

Specific Models

- The free parameters are: $g_{z'}$, λ, y_i, $U(1)'$ charges, $M_{\tilde{Z}'}$, and SUSY breaking scale Λ_S
- A simple choice (leads to a light wino, $M_2 < M_{1,3}$):
  - 3 families of colored exotics (D)
  - 2 families of uncolored $SU(2)_L$ singlet families (E)

  both have $U(1)_Y$ charge
- Superpotential

$$W = \lambda\, S\, H_u\, H_d + y_D\, S\, D\, D^c + y_E\, S\, E\, E^c + \text{quark} + \text{lepton}$$

- Taking $Q_{H_d} = 1$, Q_{H_u} and Q_Q are free parameters

  (other charges are determined by anomalies)
- Other constraints
  - $U(1)'$ spontaneously broken by radiative corrections
  - Allow appropriate fine tuning to break EW symmetry
  - Check for color or charge breaking minima

RGE running

- Very different scales

  Ideal approach: integrate out different fields at each scale

  Non trivial task

  e.g integrate out heaviest particle $\tilde{Z}'$

  $\Rightarrow$ different RGEs for Yukawas and quartic couplings

- Simplified treatment: integrate out heavy scalars and $\tilde{Z}'$ at the same scale

  disadvantage: multiple RGE threshold corrections

  Two regions $M_{\tilde{Z}'} < \mu < \Lambda_S$ and $\mu < M_{\tilde{Z}'}$

RGE running

- $M_{\tilde{Z}'} < \mu < \Lambda_S$: use usual soft SUSY RGEs

  one loop RGEs for: gauge and Yukawas, $M_{\tilde{Z}'}$ and $m_{\tilde{f}_i}$, and A terms

  two loop RGEs for gaugino masses

- $\mu < M_{\tilde{Z}'}$: SM + Higgs + gauginos

  one loop RGEs: SM Higgs and quartic, Yukawas, gauge and gaugino mass

  + Threshold corrections e.g.

$$m_H^2(\mu \approx m_{\tilde{f}_i}) = min(\mathcal{M}_H^2) - \frac{3y_t^2}{16\,\pi^2} m_{\tilde{f}_i}^2$$

Five Benchmark Models

All mass units are GeV $M_{\tilde{Z}'}$ **fixed** at 1000 TeV

	1	2	3	4	5
Q_2	$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{2}$	$-\frac{1}{2}$
Q_Q	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	-2	-2
$g_{z'}$	0.45	0.23	0.23	0.06	0.04
λ	0.5	0.8	0.8	0.3	0.3
Y_D	0.6	0.7	0.8	0.4	0.6
Y_E	0.6	0.6	0.6	0.1	0.1
$\langle S \rangle$	2×10^5	7×10^4	6×10^4	2×10^5	8×10^4
$\tan\beta$	20	29	33	45	60
M_1	2700	735	650	760	270
M_2	710	195	180	340	123
M_3	4300	1200	1100	540	200
m_H	140	140	140	140	140
$m_{\tilde{Q}3}$	1×10^5	5×10^4	4×10^4	8×10^4	4×10^4
$m_{\tilde{L}3}$	3×10^5	10^5	10^5	2×10^4	10^5
$m_{3/2}$	890	3600	810	3	0.1
$m_{\tilde{S}}$	4300	230	160	31	4
$m_{Z'}$	7×10^4	1.5×10^4	1.3×10^4	5600	2100

Combining Anomaly and Z' Mediation of SUSY Breaking

Jorge de Blas, Paul Langacker, GP, Lian-Tao Wang

JHEP **1001** 037 (2010) [arXiv:0911.1996]

Preliminary results in GP [arXiv:0910.2480]

Reminder: Z' Mediation

- Scalars get a mass at one loop

$$m^2_{\tilde{f}_i} \sim g^2_{z'} Q^2_{f_i} \frac{M^2_{\tilde{Z}'}}{16\pi^2} \log\left(\frac{\Lambda_S}{M_{\tilde{Z}'}}\right)$$

- $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauginos get a mass at two loops

$$M_a \sim g^2_{z'} g^2_a \frac{M_{\tilde{Z}'}}{(16\pi^2)^2} \log\left(\frac{\Lambda_S}{M_{\tilde{Z}'}}\right)$$

- Ratio of masses

$$\frac{m_{\tilde{f}_i}}{M_a} \sim \frac{M_{\tilde{Z}'}}{4\pi} \Big/ \frac{M_{\tilde{Z}'}}{(4\pi)^4} = (4\pi)^3 \sim 1000$$

- LEP direct searches imply EW-ino mass > 100 GeV
- Scalars at EW scale ($\sim 100 - 1000$ GeV)

  $\Rightarrow$ gauginos too light, must acquire mass from other mechanism

Combine Z' Mediation and ...

- Choosing family universal charges

  Z' coupling naturally flavor diagonal

- To avoid introducing flavor problem combine with e.g.
  - Gauge mediation
  - Gaugino mediation
  - Anomaly mediation

- Combining with gauge and gaugino mediation

  amounts to a larger gauge group

- Pure anomaly mediation has negative slepton problem

$\Rightarrow$ naturally should be combined with other mechanism

Reminder: Anomaly Mediation

- In anomaly mediated SUSY breaking

$$
\begin{aligned}
M_a &= \frac{\beta_g}{g} m_{3/2} \\
m^2 &= -\frac{1}{4}\left(\frac{\partial\gamma}{\partial g}\beta_g + \frac{\partial\gamma}{\partial y}\beta_y\right) m_{3/2}^2
\end{aligned}
$$

  where

$$
\gamma \equiv d\ln Z_Q/d\ln\mu \quad \beta_g \equiv dg/d\ln\mu \quad \beta_y \equiv dy/d\ln\mu
$$

- At one loop

$$
\gamma = \frac{1}{16\pi^2}\left(4g_a^2 C_a - |y|^2\right)
$$

- For sleptons

$$
y \sim 0, \quad \beta_g > 0, \quad \Rightarrow m^2 < 0
$$

Combining Anomaly and Z' Mediation

- Z' mediation of SUSY breaking
  - Gaugino and scalar masses generated by Z' mediation
  - Gauginos at EW scale ($\sim 100 - 1000$ GeV)

    $\Rightarrow$ scalars "too **heavy**"

    i.e. need one fine-tuning to set EW breaking scale
- Anomaly mediation
  - Slepton (squared) masses are "too **light**"

    i.e. slepton squared masses are negative
- Can we combine the two and solve both "problems"?

Combining Anomaly and Z' Mediation

- Z' mediation of SUSY breaking
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- Anomaly mediation
  - Slepton (squared) masses are "too **light**"

    i.e. slepton squared masses are negative
- Can we combine the two and solve both "problems"?
- To avoid tachyonic sleptons need $m^2_{\mathrm{AMSB}} \sim m^2_{\mathrm{ZpSB}}$

$$m^2_{\mathrm{AMSB}} \sim \frac{m^2_{3/2}}{(16\pi^2)^2} \qquad\qquad m^2_{\mathrm{ZpSB}} \sim \frac{M^2_{\tilde{Z}'}}{16\pi^2}$$

$$\Downarrow$$

$$\boxed{M_{\tilde{Z}'} \sim \frac{m_{3/2}}{4\pi}}$$

- Is such a relation feasible?

"Z' Gaugino mediation"

- Consider 5-D scenario: Z' version of MSSM gaugino mediation [Kaplan, Kribs, Schmaltz '99; Chacko, Luty, Nelson, Ponton '99]
  - Visible sector fields on one brane
  - Hidden sector fields on another brane
  - Z' propagates in the bulk
- On hidden

$$c\int d^2\theta\,\frac{X}{M_*^2}\,W_{z'}\,W_{z'}\delta(y-L)$$

M_*: 5-D planck mass, L: size of XD, $M_*^3\,L = M_p^2$

- When X develops an F term

$$M_{\tilde{Z}'} = c\frac{F_X}{M_*^2\,L}$$

while

$$m_{3/2} \sim \frac{F}{M_p} = \frac{F}{\sqrt{M_*^3\,L}}$$

- Assuming $F \sim F_X$

$$M_{\tilde{Z}'} \sim c\,\frac{m_{3/2}}{\sqrt{M_*\,L}} \overset{!}{\sim} \frac{m_{3/2}}{4\pi} \Rightarrow M_* L \sim 16\pi^2\,c^2$$

“Z’ Gaugino mediation”

- To suppress operators of the form

$$\frac{1}{M_*^2}\int d^4\theta\, Y^\dagger\, Y\, Q^\dagger\, Q$$

which lead to FCNC need $M_* L \gtrsim 16$

[Kaplan, Kribs, JHEP **0009**, 048 (2000)]

- To keep gauge coupling perturbative need $M_* L \lesssim 16\pi^2$

[Kaplan, Kribs, Schmaltz, PRD **62**, 035010 (2000)]

- For $m^2_{\mathrm{AMSB}} \sim m^2_{\mathrm{ZpSB}}$

$$M_* L \sim 16\pi^2\, c^2$$

- Conclusion: with $c \sim \mathcal{O}(1)$, easy to get right hierarchy, or

$$4 \lesssim c\,\frac{m_{3/2}}{M_{\tilde{Z}'}} \lesssim 4\pi$$

- Conclusion: MSSM gaugino masses from pure anomaly

Sfermions masses from anomaly + Z'

Specific Implementation

- Use same model as original Z' mediation

  (leads to a light wino, $M_2 < M_{1,3}$):

  - 3 families of colored exotics (D)
  - 2 families of uncolored $SU(2)_L$ singlet families (E)

  both have $U(1)_Y$ charge

- Superpotential

$$W = \lambda\, S\, H_u\, H_d + y_D\, S\, D\, D^c + y_E\, S\, E\, E^c + \text{quark} + \text{lepton}$$

- At Λ_S AMSB b.c. for M_a, m^2 , and A terms

  RGE from Λ_S to Λ_{EW} include Z' contribution

Specific Implementation

- Interesting difference from "standard" AMSB

  $\beta_3 = 0$ at one loop $\Rightarrow M_3 = 0$ at one loop

- Follows from $SU(3)_C^2 \times U(1)'$ anomaly cancellation condition

  and very general assumptions

- Including two loop effects

  $$M_1 > M_3 > M_2$$

  Wino LSP by choice of exotics

- Two loop RGEs for gauge and gauginos, one loop for all other

Scalar Potential

- "Extended" higgs sector H_u, H_d, S

  need to break $SU(2)_L \times U(1)_Y \to U(1)_{\rm em}$ and $U(1)'$
- Scalar potential:

  - Soft masses
  $$m_S^2|S|^2 + m_{H_u}^2|H_u|^2 + m_{H_d}^2|H_d|^2$$
  - MSSM D terms
  $$\frac{1}{8}(g^2 + g'^2)\left(|H_u|^2 - |H_d|^2\right)^2$$
  - $U(1)'$ D terms
  $$\frac{1}{2}g_{z'}^2\left(Q_{H_u}|H_u|^2 + Q_{H_d}|H_d|^2 + Q_S|S|^2\right)^2$$
  - F terms
  $$|\lambda|^2\left(|S|^2|H_u|^2 + |S|^2|H_d|^2 + |H_u|^2|H_d|^2\right)^2$$
  - A terms
  $$-2ASH_uH_d$$
- Typically requires vev of S larger than EW scale

Illustration point: Inputs

- Dimensionful input parameters

$$m_{3/2} = 80\,\mathrm{TeV}, \quad M_{\tilde{Z}'} = 15\,\mathrm{TeV}, \quad \Lambda_S = 10^6\,\mathrm{TeV}$$

- $U(1)'$ charges

$$Q_{H_u} = -\frac{2}{5}, \quad Q_Q = -\frac{1}{3}$$

- $U(1)'$ gauge coupling (at Λ_S)

$$g_{z'} = 0.45$$

- Superpotential

$$W = \lambda\, S\, H_u\, H_d + y_D\, S\, D\, D^c + y_E\, S\, E\, E^c + \text{quark} + \text{lepton}$$

- Super potential parameters (at Λ_{EW})

$$\begin{array}{lll} \lambda = 0.1 & y_D = 0.3 & y_E = 0.5 \\ y_t \simeq 1 & y_b = 0.5 & y_\tau = 0.294 \end{array}$$

Illustration point: Results

- "Higgs" Sector

$$\tan\beta = 29, \quad \langle S \rangle = 11.9\,\mathrm{TeV}$$

- "Higgs" particles **including one loop radiative corrections**

$$m_{h^0} = 0.138\,\mathrm{TeV}, \quad m_{H_1^0} = 2.79\,\mathrm{TeV}, \quad m_{H_2^0} = 4.78\,\mathrm{TeV}$$

- Neutralinos

$$m_{\tilde{N}_1} = 0.278\,\mathrm{TeV}\,(\text{“Wino”}), \quad m_{\tilde{N}_2} = 0.61\,\mathrm{TeV}\,(\text{“Singlino”}), \quad m_{\tilde{N}_3} = 1.15\,\mathrm{TeV}\,(\text{“Bino”})$$

$$m_{\tilde{N}_4} \sim m_{\tilde{N}_5} \sim 1.2\,\mathrm{TeV}\,(\text{“Higgsinos”}), \quad m_{\tilde{N}_6} = 12.7\,\mathrm{TeV}\,(\text{“Z}'\text{gaugino”})$$

- Charginos

$$m_{\tilde{C}_1} = 0.278\,\mathrm{TeV}\,(\text{“Wino”}), \quad m_{\tilde{C}_2} = 1.2\,\mathrm{TeV}\,(\text{“Higgsino”})$$

- Gluino

$$M_3 = 0.4\,\mathrm{TeV}$$

- Z' gauge boson

$$M_{Z'} = 2.78\,\mathrm{TeV}$$

Illustration point: Results II

- MSSM sfermions

$$\text{Lightest}: \; m_{\tilde{b}_1} \sim m_{\tilde{t}_1} = 0.7\,\text{TeV}, \quad \text{Heaviest}: \; m_{\tilde{e}_R} = m_{\tilde{\mu}_R} = 12.2\,\text{TeV}$$

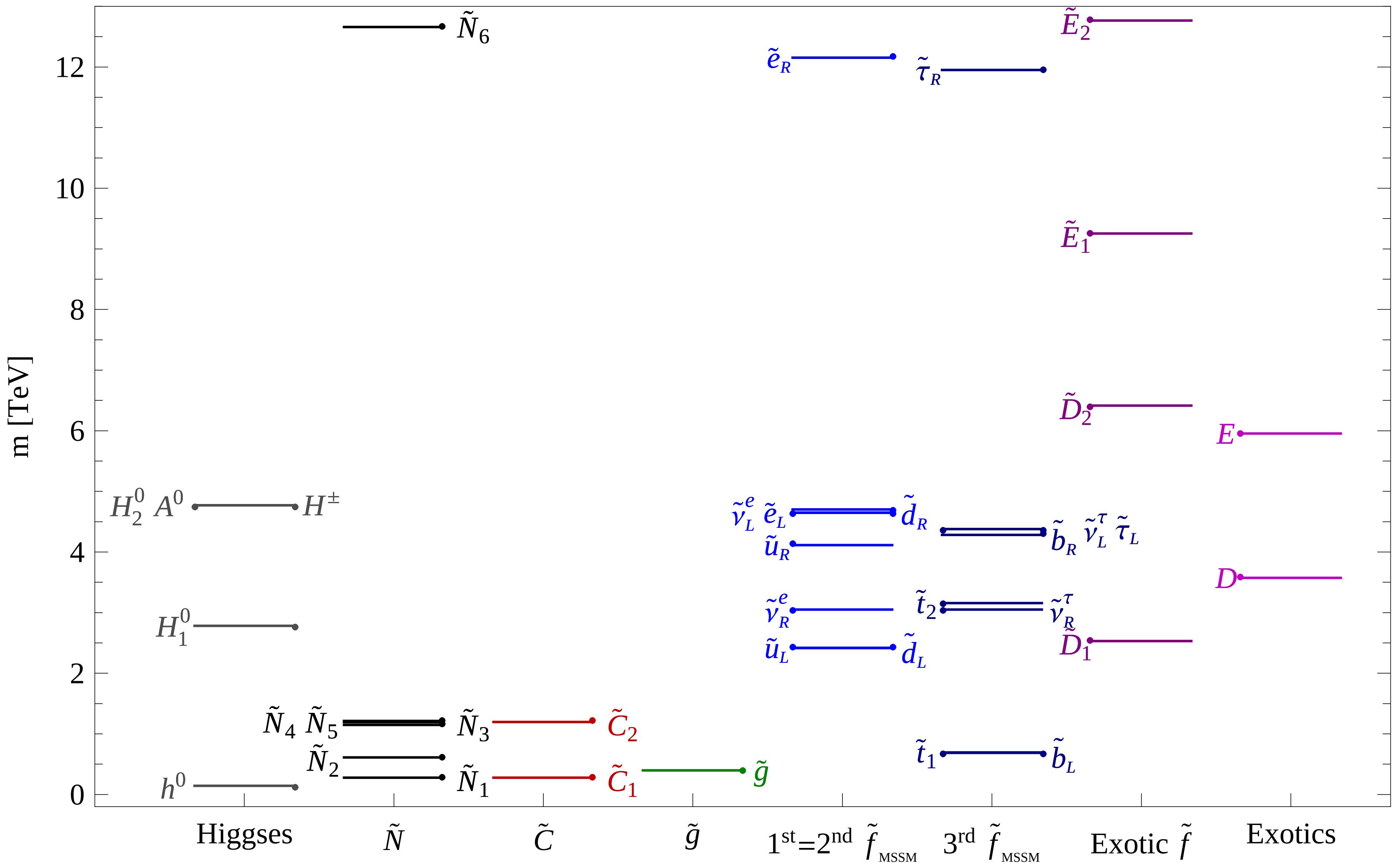
- Exotic sfermions

$$\text{Lightest}: \; m_{\tilde{D}_1} = 2.53\,\text{TeV}, \quad \text{Heaviest}: \; m_{\tilde{E}_2} = 12.8\,\text{TeV}$$

- Exotic fermions

$$m_D = 3.57\,\text{TeV}, \quad m_E = 5.95\,\text{TeV}$$

Illustration point: Spectrum



Phenomenology

- Some features of spectrum
  - A few TeV Z' gauge boson
  - Light gluino: $M_{\tilde{g}} < M_1, m_{\tilde{q}}$
  - Third generation squarks are the lightest sfermions

    negative RGE contribution from larger yukawa
- Possible signal: a few TeV Z' gauge boson
- Possible signal: gluino decay

Phenomenology

- Possible signal: gluino decay
  - Gluino can only decay to quarks and wino via off-shell squarks
  - $m_{\tilde{q}_3} < m_{\tilde{q}_{1,2}} \Rightarrow$ gluino decays to third generation squarks
  - Depending on $M_3 - M_2$, possible channels

    $b\bar{b} + \tilde{N}_0, \quad t + \bar{b} + \tilde{C}^+, \quad t\bar{t} + \tilde{N}_0$
  - For illustration point $M_3 - M_2 < m_t$

    Can also find $M_3 - M_2 > m_t$ or $M_3 - M_2 > 2m_t$ with heavier gluino

Scalar Potentials and Accidental Symmetries in Supersymmetric $U(1)'$ Models

Paul Langacker, GP, Itay Yavin

PLB **671** 245 (2009) [arXiv:0811.1196]

Gauge Unification?

- $U(1)'$ symmetry $\Rightarrow$ new anomaly cancellation condition

$$\Downarrow$$

Introduce new "exotic" matter

  - X_i charged under SM and $U(1)'$
  - SM singlet(s) S_i give mass to X_i: $SX_iX_i^c \in W$

- Problem: Typically exotics spoil MSSM unification

- Solutions:
  - Give up unification
  - Embed $G_{\text{SM}} \times U(1)'$ inside a larger group such as E_6

    $\Rightarrow$ need extra "Higsses" that reintroduce μ problem

    [Langacker and J. Wang '98]
  - Add complete $SU(5)$ multiplets of exotic matter

    different $U(1)'$ charges in the same multiplet

    $\Rightarrow$ do not descend from $SU(5) \times U(1)'$

SM Singlets

- Adding complete $SU(5)$ multiplets of exotic matter

  $$\Downarrow$$

  Must introduce more than one singlet field

  [Erler '00, Morrissey and Welsh '05]

- Singlet fields should:

  1. Break $U(1)'$ symmetry
  2. Generate effective μ term for H_u and H_d
  3. Give mass to exotic matter

Generic Problems with Multiple Singlets

- $U(1)' +$ gauge unification $\Rightarrow$ Multiple singlet fields

- Problem 1: Accidental global symmetries:

  Once broken lead to axion-like bosons

- Problem 2: Generating required vacuum structure:

  Exotics might remain massless

Problem 1: Accidental Global Symmetries

- Consider only D-terms and soft masses in scalar potential

$$V(S_1, ..., S_N) = \sum_i m_i^2 |S_i|^2 + \frac{g_{z'}^2}{2} \left(\sum_i Q_i |S_i|^2 \right)^2 .$$

- N scalar fields $\Rightarrow$ N phases

  one linear combination "eaten" by Z' gauge boson

  $\Rightarrow N-1$ "accidental" global symmetries

  If all spontaneously broken, get $N-1$ massless Nambu-Goldstone bosons

- Global symmetries anomalous under $G_{\rm SM}$

  $\Rightarrow$ one linear combination is an axion with mass $\Lambda^2_{\rm QCD}/f$

  Other bosons are massless excluded!

- Even axion problematic: For $f \sim 100$ TeV, mass ~ 100 eV

  Experimental constraint: Axion mass should be ≤ 10 meV

Breaking the Accidental Global Symmetries

- Only way out, explicitly break the $N-1$ global symmetries

  Need $N-1$ linearly independent terms in the superpotential
- Ideally use only cubic terms: $S_i S_j S_k, S_i^2 S_j \in W$

  unlike bilinear terms $\mu S_i S_j \in W$ do not require mass scale μ
- Can we use only cubic terms?

Example: Erler's Model

- MSSM + Exotics: two pairs of $\mathbf{5}+\mathbf{5}^*$: (D_i, L_i) and (D_i^c, L_i^c), $i=1,2$

  need two singlets: S, S_D with charges $Q_S = 1 \quad Q_{S_D} = 3/2$

  S generates μ term and give mass to L, L_c, S_D give mass to D, D^c

- 2 Singlets $\Rightarrow$ 1 accidental symmetry

  With only S and S_D **no** superpotential terms allowed

Example: Erler's Model

- MSSM + Exotics: two pairs of $\mathbf{5}+\mathbf{5}^*$: (D_i, L_i) and (D^c_i, L^c_i), $i=1,2$

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- 2 Singlets $\Rightarrow$ 1 accidental symmetry

  With only S and S_D **no** superpotential terms allowed

- Let's add another singlet S_1

  3 Singlets: $S, S_D, S_1 \Rightarrow$ 2 accidental symmetries

  Can write **1** superpotential term

  $S S_D S_1$ **or** $S S S_1$ **or** $S_D S_D S_1$

Example: Erler's Model

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  3 Singlets: $S, S_D, S_1 \Rightarrow$ 2 accidental symmetries

  Can write **1** superpotential term

  SS_DS_1 **or** SSS_1 **or** $S_DS_DS_1$

- Let's add another singlet S_2

  4 Singlets: $S, S_D, S_1, S_2 \Rightarrow$ 3 accidental symmetries

  Can write **2** superpotential terms

Example: Erler's Model

- MSSM + Exotics: two pairs of $\mathbf{5}+\mathbf{5}^*$: (D_i, L_i) and (D_i^c, L_i^c), $i=1,2$

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  Can write **2** superpotential terms

- Let's add another singlet...

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- Let's add another singlet S_2

  4 Singlets: $S, S_D, S_1, S_2 \Rightarrow$ 3 accidental symmetries

  Can write **2** superpotential terms

- Let's add another singlet...

- Can we use only cubic terms?

Bilinear Terms

- If using only cubic terms might need to add a large # of singlets
- Might want to use bilinear terms $\mu S_i S_j \in W$
- Does this reintroduce the μ problem?

Bilinear Terms

- If using only cubic terms might need to add a large # of singlets
- Might want to use bilinear terms $\mu S_i S_j \in W$
- Does this reintroduce the μ problem?

NO!

- μ problem: have μ in $\mu H_u H_d \in W$ at the same scale

  as the soft parameters (b, $m^2_{H_u}$, $m^2_{H_d}$)
- Here not using μ term to generate vacuum structure

  Need μ to give mass larger than MeV

Example: Erler's Model

- MSSM + Exotics: two pairs of $\mathbf{5}+\mathbf{5}^*$: (D_i, L_i) and (D_i^c, L_i^c), $i = 1, 2$

  need two singlets: S, S_D with charges $Q_S = 1 \quad Q_{S_D} = 3/2$

  S generates μ term and give mass to L, L_c, S_D give mass to D, D^c

- Using only cubic terms requires 4 extra singlets

  The superpotential terms are:

$$S_1 S_1 S_2,\ S_2 S_3 S_D,\ S_1 S_4 S_D,\ S S_3 S_3, S S S_4$$

- With bilinears can do with only 2 extra singlets

$$\mu S S_1 + y_1 S_1 S_2 S_D + y_2 S S_2 S_2 \in W$$

  New singlets' charges $Q_{S_1} = -1 \quad Q_{S_2} = -1/2$

Problem 2: required vacuum structure

- Need to give vacuum expectation value (vev) to multiple scalars. How?
- No "rigorous" proofs but the big picture is:
- Easier to analyze by ignoring F terms for now

$$V(S_1, ..., S_N) = \sum_i m_i^2 \left|S_i\right|^2 + \frac{g_{z'}^2}{2} \left(\sum_i Q_i \left|S_i\right|^2 \right)^2 .$$

- Reasonable to assume some m_i^2 are driven negative by RGEs
- Consider two cases
  1. Only one fields develop a vev
  2. "Flat" direction
- First case:
  - If for only one field $m_i^2 < 0$, it will develop a vev
  - If multiple fields have $m_i^2 < 0$,
    only the field with largest $|m_i^2/Q_i|$ develop a vev

"Flat" direction

- Assume that for two fields with opposite charges S_i and S_j

  $|Q_j|m_i^2 + |Q_i|m_j^2 < 0$

  $\Rightarrow$ "runaway" direction: $V \to -\infty$, for $|Q_i||S_i|^2 = |Q_j||S_j|^2 \to \infty$
- Adding F terms stabilize the vevs at finite values

  $\Rightarrow$ Generate vevs for S_i and S_j
- After "vacuum insertion" A terms can generate linear terms

  in the potential for other fields: $A\,|S_i|\,|S_j|\,S_m \in V$

  $\Rightarrow$ generate vev for S_m
- This case is phenomenologically favorable

Example: Erler's Model

- Recall superpotential

$$\mu S S_1 + y_1 S_1 S_2 S_D + y_2 S S_2 S_2 \in W$$

and charges: $Q_{S_1} = -1 \quad Q_{S_2} = -1/2 \quad Q_S = 1 \quad Q_{S_D} = 3/2$

- We need S and S_D to develop a vev

For simplicity ignore μ term and assume $y_1 \ll y_2,\ g_{z'}$

Scalar potential ("turning off" A terms)

$$V(S, S_D, S_1, S_2) = \sum_i m_i^2 |S_i|^2 + \frac{g_{z'}^2}{2}\left(\sum_i Q_i |S_i|^2\right)^2 + |y_2|^2 |S_2|^4$$

- Flat direction for S_2 and S_D, assume

$|Q_{S_1}| m_{S_D}^2 + |Q_{S_D}| m_{S_1}^2 > 0$ and $|Q_{S_2}| m_{S_D}^2 + |Q_{S_D}| m_{S_2}^2 < 0$

- The vevs are

$$|S_D|^2 = -\frac{4}{9}\frac{m_{S_D}^2}{g_{z'}^2} - \frac{1}{18 y_2^2}\left(3 m_{S_2}^2 + m_{S_D}^2\right) \qquad |S_2|^2 = -\frac{1}{6 y_2^2}\left(3 m_{S_2}^2 + m_{S_D}^2\right)$$

Notice $|S_i| \propto 1/y_2^2$ remnant of the flat direction

Example: Erler's Model

- S_2 and S_D have vevs
- Recall superpotential

$$\mu S S_1 + y_1 S_1 S_2 S_D + y_2 S S_2 S_2 \in W$$

- "Turn on" A term for $S S_2 S_2$

  linear term for S: $A\, S|S_2|^2 \in V$

  $\Rightarrow$ generate vev for S
- Final result: both S and S_D have vevs $\surd$

Conclusions

Future Directions

- Other Z' mediation models:

  Models with gauge unification?

  Implement Erler's model

  Models with wino/bino LSP?

- Incorporate in other top-down models

- Models of the hidden sector:

  "Z' gaugino mediation"

Conclusions

1) Motivated by top-down constructions, Z' mediation:

   mechanism for mediation of SUSY breaking via a $U(1)'$ gauge interaction

- Specific implementation
  - heavy sfermions, Higgsinos, exotics $\sim$ 10 - 100 TeV
  - Light gauginos $\sim 100 - 1000$ GeV, of which the lightest can be wino-like and a light Higgs $\sim$ 140 GeV

Conclusions

1) Motivated by top-down constructions, Z' mediation:

   mechanism for mediation of SUSY breaking via a $U(1)'$ gauge interaction

- Specific implementation
  - heavy sfermions, Higgsinos, exotics $\sim$ 10 - 100 TeV
  - Light gauginos $\sim 100 - 1000$ GeV, of which the lightest can be wino-like and a light Higgs ~ 140 GeV

2) Combining Z' mediation with AMSB allows us to
  - Avoid fine tuning for Z' mediation
  - Solve AMSB's tachyonic slepton problem

- Require

$$M_{\tilde{Z}'} \sim \frac{m_{3/2}}{4\pi}$$

  can be obtained from 5-D UV completion

- Specific implementation
  - Wino LSP but $M_1 > M_3 > M_2$
  - $M_{Z'} \sim 2.8$ TeV
  - Sfermions, exotic fermions $1 - 10$ TeV
  - Light gluino decays to third generation quarks

Conclusions

3) $U(1)' +$ gauge unification $\Rightarrow$ Multiple singlet fields

Generic problems:

- accidental symmetries $\Rightarrow$ light bosons
  - Solution: explicitly breaking via SP terms

    Cubic might not be feasible, bilinears OK
- Vacuum structure: multiple scalar vevs
  - Solution: lifted flat direction: two scalar vevs

    A terms $\Rightarrow$ more vevs

Conclusions

3) $U(1)' +$ gauge unification $\Rightarrow$ Multiple singlet fields

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- Vacuum structure: multiple scalar vevs
  - Solution: lifted flat direction: two scalar vevs

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4) More work to be done!

Backup Slides

Z' Mediation of SUSY Breaking: Phenomenology

Paul Langacker, GP, Lian-Tao Wang, Itay Yavin

PRL **100** 041802 (2008) [arXiv:0710.1632]
PRD **77** 085033 (2008) [arXiv:0801.3693]

Phenomenology

- Full discussion in

  P. Langacker, GP, L.T. Wang and I. Yavin

  PRD **77** 085033 (2008) [arXiv:0801.3693]

- Here discuss

  - Higgs Mass
  - Gluino Decay
  - Ino spectra

Higgs Mass

	1	2	3	4	5
Q_2	$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{2}$	$-\frac{1}{2}$
Q_Q	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	-2	-2
$g_{z'}$	0.45	0.23	0.23	0.06	0.04
λ	0.5	0.8	0.8	0.3	0.3
Y_D	0.6	0.7	0.8	0.4	0.6
Y_E	0.6	0.6	0.6	0.1	0.1
$\langle S \rangle$	2×10^5	7×10^4	6×10^4	2×10^5	8×10^4
$\tan\beta$	20	29	33	45	60
M_1	2700	735	650	760	270
M_2	710	195	180	340	123
M_3	4300	1200	1100	540	200
m_H	140	140	140	140	140
$m_{\tilde{Q}_3}$	1×10^5	5×10^4	4×10^4	8×10^4	4×10^4
$m_{\tilde{L}_3}$	3×10^5	10^5	10^5	2×10^4	10^5
$m_{3/2}$	890	3600	810	3	0.1
$m_{\tilde{S}}$	4300	230	160	31	4
$m_{Z'}$	7×10^4	1.5×10^4	1.3×10^4	5600	2100

Higgs Mass

- At low energies, one light Higgs $m_H^2 = 2\lambda_H v^2$ ($v = 174$ GeV)
- λ_H determined by matching at $M_{\tilde{Z}'}$ and running down to EW scale:

$$
\begin{aligned}
16\pi^2 \frac{d\lambda_H}{dt} &= 12\left(\lambda_H^2 + \lambda_H y_t^2 - y_t^4\right) \\
\lambda_H(\mu \approx M_{\tilde{Z}'}) &= \frac{1}{4}(g_2^2 + g_Y^2) + g_{z'}^2 Q_2^2 + \frac{1}{2}\lambda^2 \sin^2 2\beta
\end{aligned}
$$

- But
  - F-term $\lambda^2 \sin^2 2\beta$ negligible ($\tan\beta \gg 1$)
  - $U(1)'$ D-term $< SU(2) \times U(1)_Y$ D-term ($g_{z'}$, Q_2 small)

  $\Rightarrow$ m_H insensitive to the precise details of the high-energy parameters

- m_H affected by running from $M_{\tilde{Z}'}$ down to EW scale

$\Rightarrow$ $m_H \sim 140$ GeV with few % uncertainty from precise matching and value of $M_{\tilde{Z}'}$ (fixed at $M_{\tilde{Z}'} = 1000$ TeV for concreteness)

Gluino Decay

	1	2	3	4	5
Q_2	$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{2}$	$-\frac{1}{2}$
Q_Q	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	-2	-2
$g_{z'}$	0.45	0.23	0.23	0.06	0.04
λ	0.5	0.8	0.8	0.3	0.3
Y_D	0.6	0.7	0.8	0.4	0.6
Y_E	0.6	0.6	0.6	0.1	0.1
$\langle S\rangle$	2×10^5	7×10^4	6×10^4	2×10^5	8×10^4
$\tan\beta$	20	29	33	45	60
M_1	2700	735	650	760	270
M_2	710	195	180	340	123
M_3	4300	1200	1100	540	200
m_H	140	140	140	140	140
$m_{\tilde{Q}_3}$	1×10^5	5×10^4	4×10^4	8×10^4	4×10^4
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Gluino Decay

- 3-body decay via off-shell squark : $\tilde{g} \to q\ \bar{q}\ \tilde{\chi}_i$

  i.e. via dimension 6 operator $(\bar{q}\,\tilde{g})(\tilde{\chi}_i\,q)$

$$\tau_3 = 4 \times 10^{-16}\text{sec}\ \left(\frac{m_{\tilde{Q}}}{10^2\ \text{TeV}}\right)^4 \left(\frac{1\ \text{TeV}}{M_3}\right)^5\ \propto\ \frac{1}{g_{z'}^6}$$

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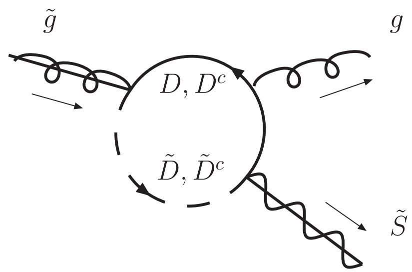
- 2-body decay $\tilde{g} \to \widetilde{S}\ g$

  i.e. via loop suppressed dimension 5 operator $\bar{\tilde{S}}\sigma^{\mu\nu}\gamma_5\tilde{g}^a G^a_{\mu\nu}$



$$\tau_2 \approx \frac{8}{n_D^2} 10^{-18}\text{sec}\left(\frac{m_D}{10^2\ \text{TeV}}\right)^2 \left(\frac{1\ \text{TeV}}{M_3}\right)^3$$

Gluino Decay

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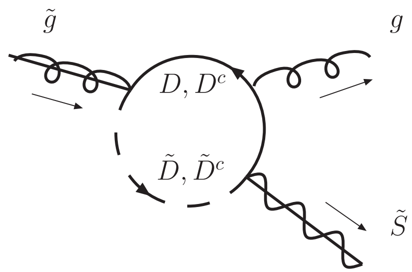

$$\tau_2 \approx \frac{8}{n_D^2}10^{-18}\text{sec}\left(\frac{m_D}{10^2\ \text{TeV}}\right)^2\left(\frac{1\ \text{TeV}}{M_3}\right)^3$$

sec	1	2	3	4	5
τ_2	$9 \cdot 10^{-13}$	$8 \cdot 10^{-19}$	$6 \cdot 10^{-19}$	$6 \cdot 10^{-15}$	$5 \cdot 10^{-14}$
τ_3	$4 \cdot 10^{-19}$	$7 \cdot 10^{-18}$	$7 \cdot 10^{-18}$	10^{-16}	10^{-15}

Ino Spectra

	1	2	3	4	5
Q_2	$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{2}$	$-\frac{1}{2}$
Q_Q	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	-2	-2
$g_{z'}$	0.45	0.23	0.23	0.06	0.04
λ	0.5	0.8	0.8	0.3	0.3
Y_D	0.6	0.7	0.8	0.4	0.6
Y_E	0.6	0.6	0.6	0.1	0.1
$\langle S \rangle$	2×10^5	7×10^4	6×10^4	2×10^5	8×10^4
$\tan\beta$	20	29	33	45	60
M_1	2700	735	650	760	270
M_2	710	195	180	340	123
M_3	4300	1200	1100	540	200
m_H	140	140	140	140	140
$m_{\tilde{Q}_3}$	1×10^5	5×10^4	4×10^4	8×10^4	4×10^4
$m_{\tilde{L}_3}$	3×10^5	10^5	10^5	2×10^4	10^5
$m_{3/2}$	890	3600	810	3	0.1
$m_{\tilde{S}}$	4300	230	160	31	4
$m_{Z'}$	7×10^4	1.5×10^4	1.3×10^4	5600	2100

Ino Spectra

Lightest inos : wino, singlino, and possibly gravitino

- Choice of exotics $\Rightarrow$ of the gauginos, wino is the lightest

  Dark matter density too low

- Gravitino mass $m_{3/2} \sim F/M_P$

$$\text{At } \Lambda_S : \qquad M_{\tilde{Z}'} \sim \frac{g_{z'}^2}{16\pi^2}\frac{F}{M}$$

  Assuming $\sqrt{F} \sim M \sim \Lambda_S$, $\sqrt{F} \sim 10^7 - 10^{11}$ GeV

  Λ_S is constrained logarithmically by the requirement of radiative symmetry breaking

  $\Rightarrow m_{3/2}$ is exponentially sensitive to the choice of model parameters

- Interesting LHC phenomenology:
  - Wino LSP only
  - Wino NLSP and Singlino LSP
  - Singlino NLSP and Wino LSP

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Ino Phenomenology

- Wino LSP only

  Decay $\tilde{W}^+ \to \tilde{W}^0 + \pi^+$ results in displaced vertex

- Wino NLSP and Singlino LSP

  wino can decay to singlino via mixing with Higgsinos, $\widetilde{W} \to h + \widetilde{S}$

$$\tau \sim 10^{-17}\text{sec}\left(\frac{100\text{ GeV}}{M_{\tilde{W}}}\right)$$

- Singlino NLSP and Wino LSP

  similar lifetime with reversed process $\widetilde{S} \to h + \widetilde{W}$

  singlino produced by $Z' \to \widetilde{S}\widetilde{S}$

“Anomaly” mediation of SUSY breaking

AMSB

- Anomaly Mediation of SUSY breaking

  [Randall, Sundrum '98 ; Giudice, Luty, Murayama, Rattazzi '98]

- "Anomaly" refers to a case where rescaling anomaly in the supergravity Lagrangian gives the dominant contributions to soft masses

- Usually derived as
  - Use a formulation of supergravity where Planck mass related to vev of scalar component of compensator field Φ
  - In presence of SUSY breaking, Φ gets an F term

$$\Phi = 1 - m_{3/2}\,\theta^2$$

  - Soft masses arise from kinetic term e.g.

$$\mathcal{L}_{\text{kin}} = \int d^4\theta\, Z_Q(\mu)\, Q^\dagger Q$$

  - Assume

$$\mu \to \frac{\mu}{\sqrt{\Phi^\dagger \Phi}}$$

AMSB

– Bringing the field to a canonical form and expanding in components generates the soft scalar masses

$$m^2 = -\frac{1}{4}\left(\frac{\partial\gamma}{\partial g}\beta_g + \frac{\partial\gamma}{\partial y}\beta_y\right) m_{3/2}^2$$

where $\gamma \equiv d\ln Z_Q/d\ln\mu$

– Similar method can be applied to gauge kinetic terms leading to gaugino masses.

Comments:

- Usual derivation criticized in [Dine, Seiberg JHEP **0703**, 040 (2007)]

  "We stress that this phenomenon is of a type familiar in field theory, and does not represent an anomaly, nor does it depend on supersymmetry breaking and its mediation."

- Usual derivation hides the fact that a special, "sequestered", form of the Kähler potential for the visible and hidden sectors is needed. This was also emphasized in [Dine, Seiberg '07]. This form arises naturally from XD models.

- Regardless of the derivation, it universally agreed that the expressions for the soft masses are correct...

Linear Equations over Finite Algebraic Field

Paul Langacker, GP, Itay Yavin

PLB **671** 245 (2009) [arXiv:0811.1196]

Interlude: Linear Equations over Finite Algebraic Field

- Given k singlets with $U(1)'$ charges $Q_1 ... Q_k$

  find l singlet fields with charges $Q_{k+1} ... Q_{k+l}$ $\quad N = k + l$

  such that $Q_1 ... Q_{k+l}$ are the solution on $k + l - 1$ linear equations

  $S_i S_j S_m \Rightarrow Q_i + Q_j + Q_m = 0$ or $S_i^2 S_j \Rightarrow 2Q_i + Q_j = 0$

- In matrix form:

$$\begin{pmatrix} 1 & 1 & 1 & 0 & ... & 0 \\ 2 & 1 & 0 & 0 & ... & 0 \\ . & & & & & \\ . & & & & & \\ . & & & & & \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} Q_1 \\ Q_2 \\ . \\ . \\ . \\ Q_N \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ . \\ . \\ . \\ 0 \end{pmatrix}$$

- Consider equations over $\mathbb{F}_3$, **Algebraic** field with 3 elements: $\{0, 1, 2\}$

  or $Q_i \to Q_i \bmod 3$

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- **Assuming** $N-1$ linearly independent equations in $\mathbb{R}$

  also linearly independent in $\mathbb{F}_3$, can immediately find the solution

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Interlude: Linear Equations over Finite Algebraic Field

- **If** assumption was correct all $U(1)'$ charges

  either **all** 1 mod 3 or **all** 2 mod 3

- In general assumption is not correct

  still, if initial set of charges $\in$ same equivalence class

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  $\Rightarrow$ easier to find enough cubic terms in superpotential

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  - $2Q_i + Q_j = 0$ connect charges of the **same** equivalence class

    $$2 \times 0 + 0 = 0 \bmod 3 \quad 2 \times 1 + 1 = 0 \bmod 3 \quad 2 \times 2 + 2 = 0 \bmod 3$$

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  - or connect charges from **three** different classes: $0 + 1 + 2 = 0 \bmod 3$
- Conclusion: If using only cubic terms

  might need to add a large # of singlets